Benefits of Inclusion of Geosynthetic Products in Reinforcement of Flexible Airfield Pavements Using Three-Dimensional Finite Element Modeling

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Objectives

- Determine benefits provided by geosynthetic reinforcement to flexible pavements
- 3D finite element model
  – Membrane and interface elements used for modeling geosynthetic material and its geomaterial interaction
- Evaluate most relevant properties

Traffic Benefit Ratio

- Assess effectiveness of a geosynthetic material in extending pavement service life
  - Defined as the ratio of the number of load cycles on a reinforced section to reach a defined failure state to the number of load cycles on an unreinforced section, with the same geometry and material constituents, to reach the same defined failure state

$$TBR = \frac{N_{\text{geogrid reinforced}}}{N_{\text{unreinforced}}}$$

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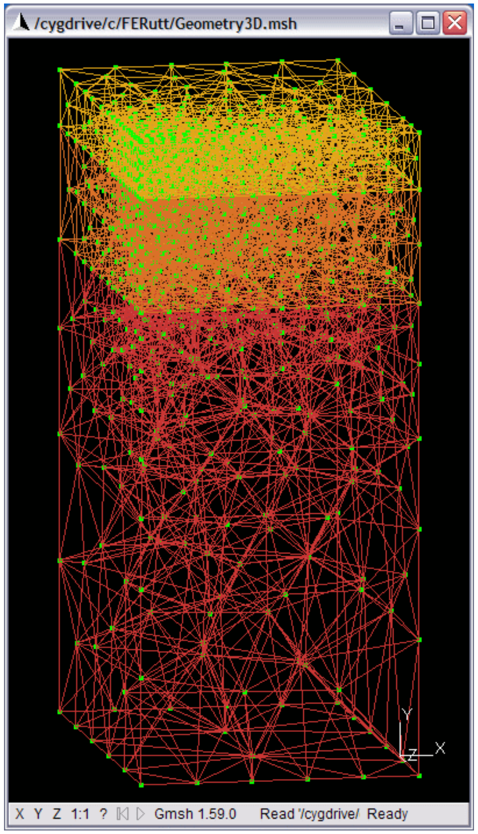
Finite element model

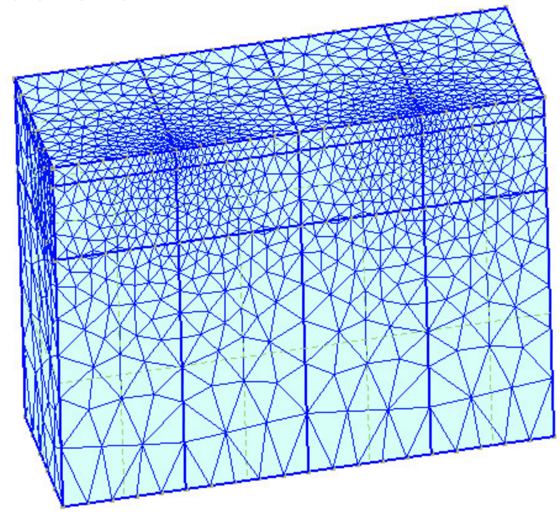
- Use of available FEA software
  - 3-D FE code, suitable for flexible pavement analysis
  - Linear or nonlinear analysis
    - Nonlinear
      - Based on a modified linear elastic behavior
      - Endorses a universal relationship for both fine and coarse grained base and subgrade material (Uzan, 1985)

$$\boxed{E = k_1 \sigma_c^{k_2} \sigma_d^{k_3}}$$

    - E : resilient modulus
    - σ_c : confining pressure
    - σ_d : deviatoric stress
    - k_1, k_2, k_3 : coefficients statistically determined from results of laboratory resilient modulus tests.



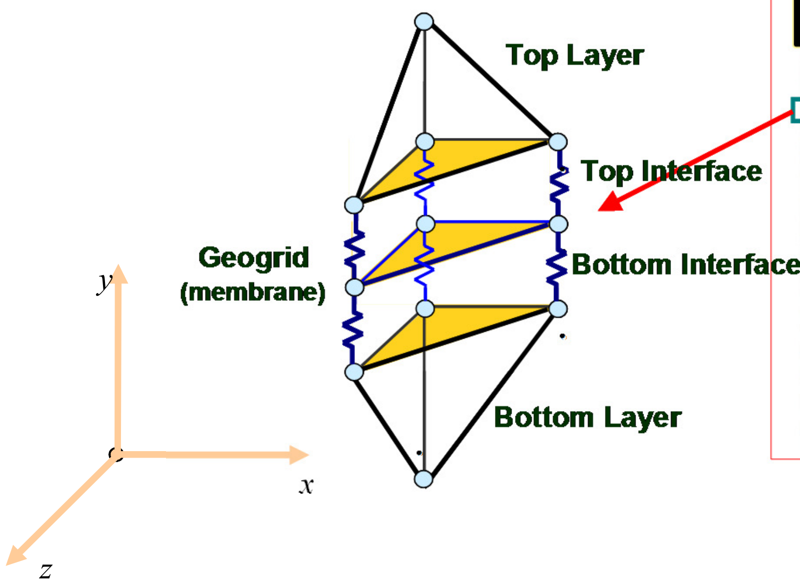
3-D Finite Element Model

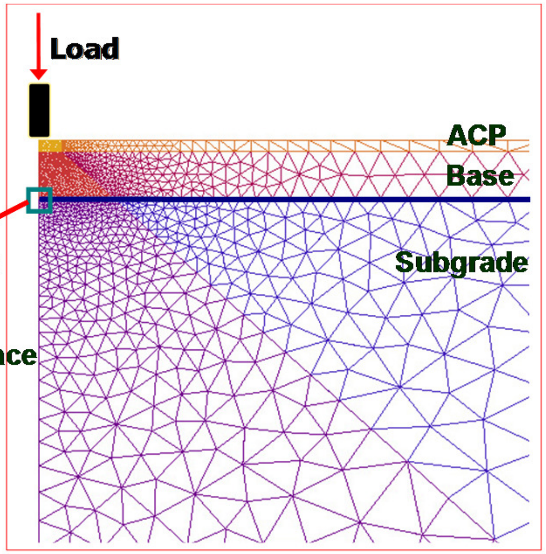


- Simulate both reinforced and unreinforced pavement sections
  - Mesh generated based on axle configuration
  - Four-node tetrahedral elements mesh
- Justification for using 3D analysis to model the pavement system
  - It better reflects the complex behavior of the composite pavement system materials
  - Preferred for the verification of the numerical model results with laboratory or field test
  - Capable of simulating the rectangular footprint of the loaded wheel

Geosynthetic Materials

- Geomembrane modeled by a three-noded triangular membrane element
- Geogrid membrane element consist of three nodes
- Interface elements used for soil-geogrid interaction





Approach

- Include membrane and interface elements to model geogrid and soil-geogrid interaction, respectively.
- Geogrid membrane element (plane stress)
- Interface element linear elastic relation
  - Shear stiffness, k_s
  - Normal stiffness, k_n
  - Displacement components u, v, w.

$$\boxed{\begin{Bmatrix} d\sigma_n \\ d\tau_x \\ d\tau_z \end{Bmatrix} = \begin{bmatrix} k_n & 0 & 0 \\ 0 & k_s & 0 \\ 0 & 0 & k_s \end{bmatrix} \begin{Bmatrix} dv \\ du \\ dw \end{Bmatrix}}$$

Pavement distress models

- Rutting model
  - Progress of rutting with load repetition
    - ε_p : accumulated permanent strain
    - ε_r : resilient elastic strain
    - N : load cycle number
    - Material parameters
      - α : rate of increase in permanent deformation against the number of load applications
      - μ : permanent deformation

$$\boxed{\varepsilon_p = \frac{\mu}{1-\alpha} \cdot \varepsilon_r \cdot N^{1-\alpha}}$$

  - Difference in deflections of the top and bottom of the layer
- Failure criterion: 1-in. rutting

Pavement distress models

- Fatigue cracking generated from tensile strains occurring at the bottom of the asphalt layers
- Fatigue model
  - N_f: the number of load applications to failure

$$\boxed{N_f = k_1 \varepsilon_t^{-k_2} E_{ACP}^{-k_3}}$$

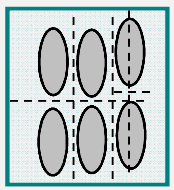
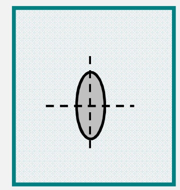
  - $k_1 = 0.0796$, $k_2 = 3.291$, and $k_3 = 0.854$ are regression parameters based on a 20% failure area criterion and standard mix asphalt

Parametric studies

- Variation in layer thickness & geosynthetic location
- Utilization of C-17 and F-15 aircrafts
- Consideration of both biaxial and triaxial geogrids
- Rutting failure criteria of 1 inch
- Effectiveness of geosynthetic determined via traffic benefit ratio (TBR)
- Linear vs. non-linear
- Impact of base and subgrade modulus

In this study, the TBR values were determined based on the rut depth of 1 in. (25 mm) since failure in rutting occurred long before failure was reached in fatigue cracking for any of the pavements analyzed in this study.

Details of Aircraft Gears

Parameter	Aircraft type	
	C-17	F-15E Eagle
Maximum takeoff weight	585,000 lb (2600 kN)	81,000 lb (360 kN)
Landing gear designation and configuration	TRT - triple tandem tricycle  	S – Single wheel  
Landing gear load	269,217 lb (1200 kN)	70,470 lb (313.5 kN)
Strut spacing	93 in. (2.36 m)	-
Tire spacing	42 in. (1.07 m)	-
Dimensions	22.8 in. × 13.8 in. (580 mm × 350.5 mm)	13.4 in. × 8.1 in. (340 mm × 206 mm)
Contact area	314 in^2 (202,580 mm^2)	108.5 in^2 (69,700 mm^2)
Tire pressure	140 psi (965 kPa)	325 psi (2240 kPa)

Geogrids

- Geogrids considered for parametric studies

Type	Parameter	Properties	
		Machine Direction (MD)	Cross Machine Direction (XMD)
Biaxial	Minimum rib thickness	1.27 mm (0.05 in.)	1.27 mm (0.05 in.)
	Tensile strength @2% strain	6.0 kN/m (410 lb/ft)	9.0 kN/m (620 lb/ft)
	Aperture stability	650 N-mm/deg (5.7 lb-in./deg)	
Triaxial	Mid-rib depth	1.2 mm (0.05 in.)	1.2 mm (0.05 in.)
	Mid-rib width	1.1 mm (0.04 in.)	1.1 mm (0.04 in.)
	Tensile strength @0.5% strain	1.1 kN/m (77 lb/ft)	
	Aperture stability	300 N-mm/deg (2.6 lb-in./deg)	

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Geogrids: Linear Elastic Properties

- Elastic modulus of the geogrid, E_g, is determined from the tensile stiffness, J_g, and the geogrid thickness, t, using
  - where J_g can be estimated from the tensile strength, $T_{\varepsilon a}$, at a certain level of axial strain, ε_a, from
  - and the geogrid shear modulus, G (kPa), is related to the measured aperture stability modulus, ASM (N-mm/degree) of the geosynthetics by

$$E_g = \frac{J_g}{t}$$

$$J_g = \frac{T_{\varepsilon_a}}{\varepsilon_a}$$

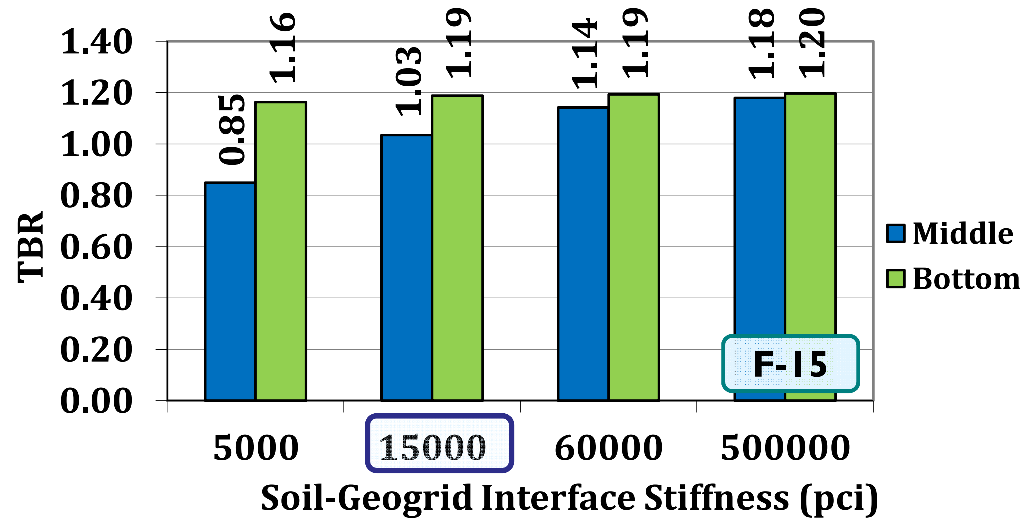
$$G = 7\,ASM$$

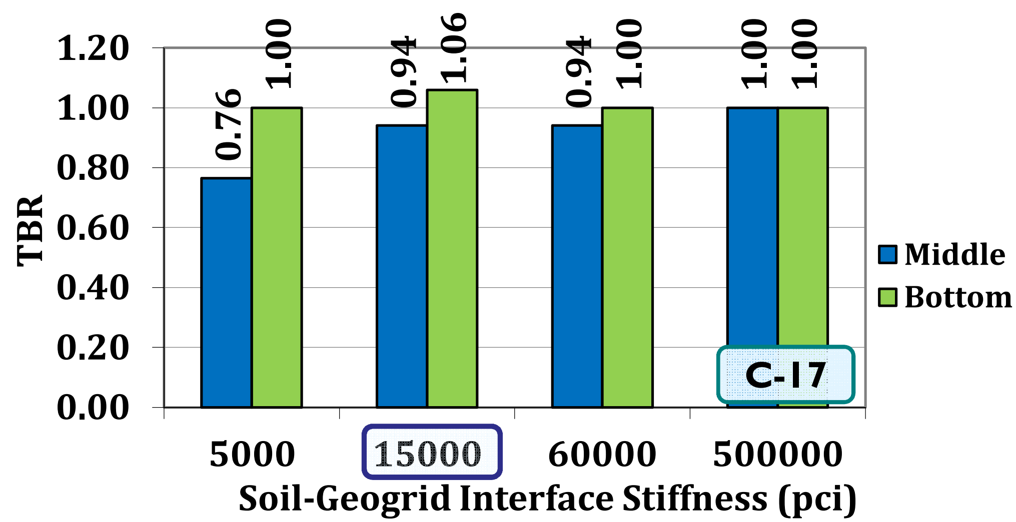
- Geosynthetic tensile properties

Parameter	Geosynthetic	
	Biaxial	Triaxial
Modulus in machine direction, E_m	34 ksi (236 MPa)	26 ksi (177 MPa)
Modulus in cross machine direction, E_{xm}	52 ksi (356 MPa)	26 ksi (177 MPa)
Poisson's ratio in cross-machine – machine direction, $\nu_{xm\text{-}m}$	0.25	0.25
Geogrid shear modulus in cross-machine – machine plane, $G_{xm\text{-}m}$	660 psi (4550 kPa)	305 psi (2100 kPa)

Soil-Geogrid Interface Shear Stiffness k_s

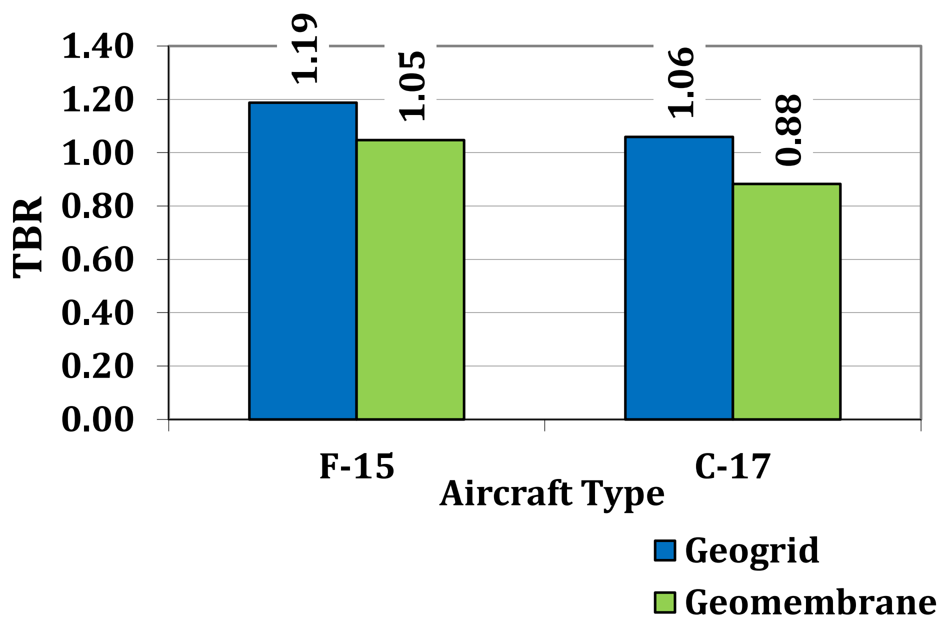
- Traffic Benefit Ratio (TBR)
  - 3-in. asphalt
  - 10-in. base
  - Varying k_s
- TBR is very sensitive to k_s when geogrid is placed at the mid-depth of the base
- Geogrids not effective in mitigating rutting for C-17





Geotextiles vs. Geogrids

- Aperture size
  - Interlocking of base course aggregates
  - Geotextiles lack this feature
    - Prevent mixing of subgrade soil and granular base material
- Geogrids provide greater shear stiffness
- No benefit of geotextile materials



Type	Parameter	Properties	
		Machine Direction (MD)	Cross Machine Direction (XMD)
Geotextile: Amoco 2006	Tensile strength @2% strain	4.25 kN/m (290 lb/ft)	13.6 kN/m (930 lb/ft)
	Aperture stability	None	

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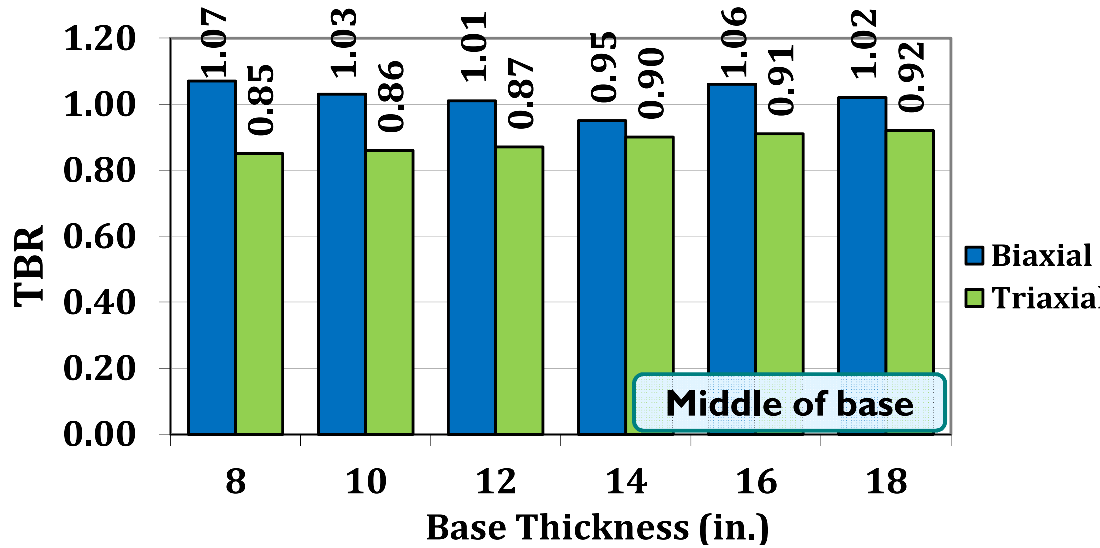
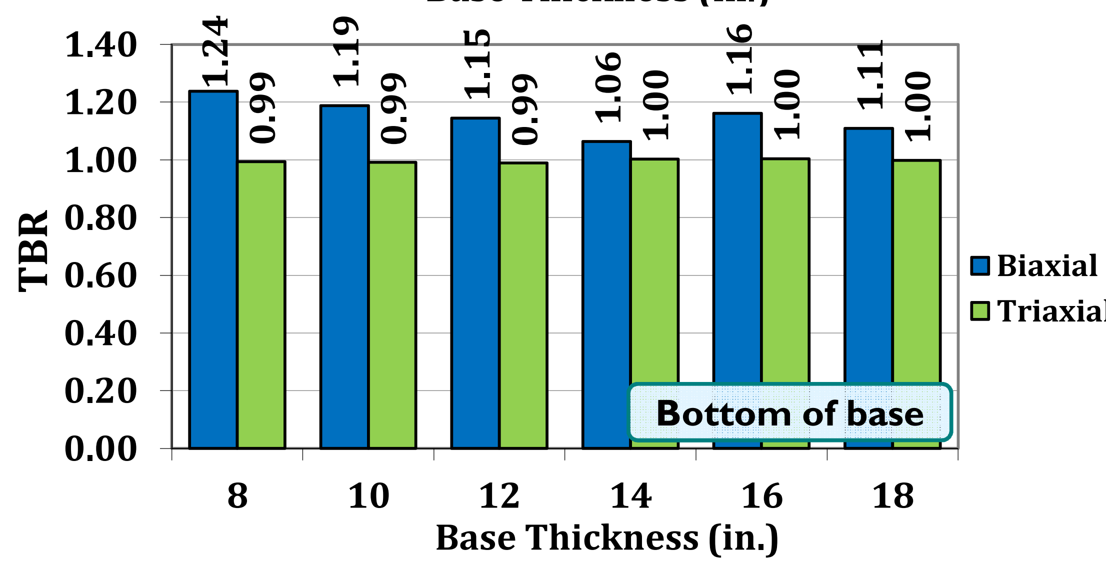
Biaxial vs. Triaxial (F-15 Aircraft)

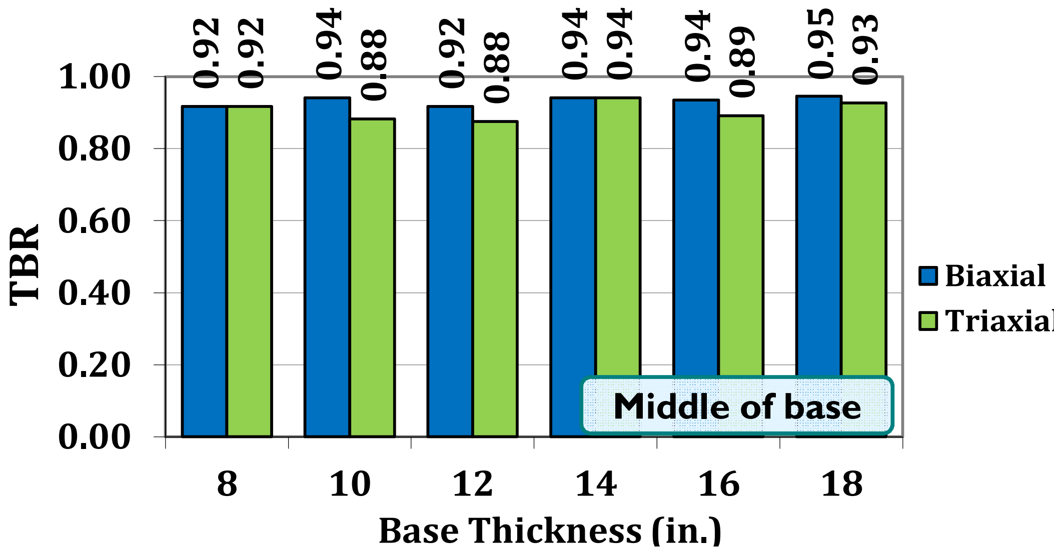
- F-15 Aircraft
- Traffic Benefit Ratio (TBR)
  - 3-in. asphalt
  - Varying base thickness
- Weaker properties of triaxial geogrid

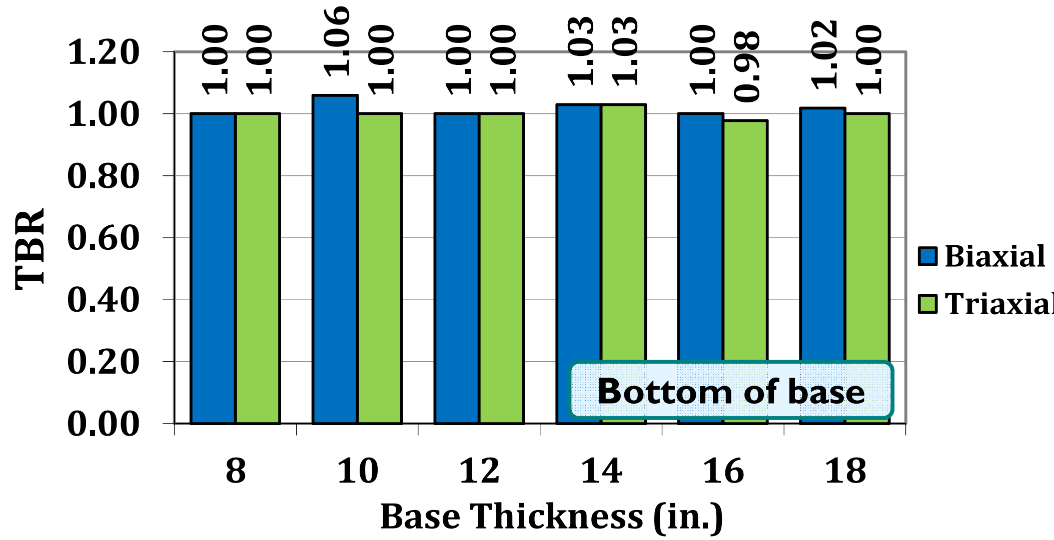




Biaxial vs. Triaxial (C-17 Aircraft)

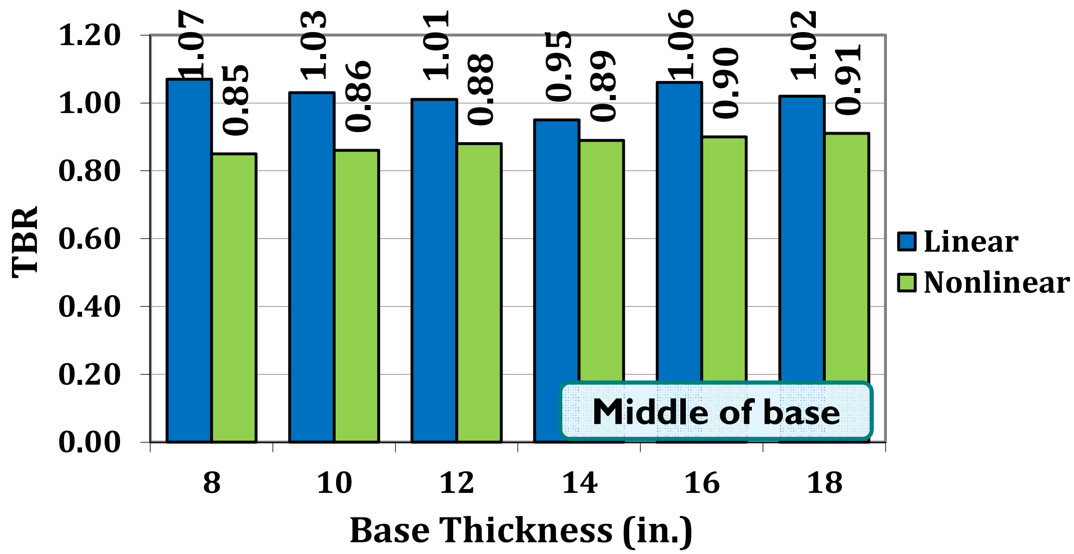
- C-17 Aircraft
- Traffic Benefit Ratio (TBR)
  - 3-in. asphalt
  - Varying base thickness
- No clear benefit when heavy loads with large contact areas are applied to the pavement.

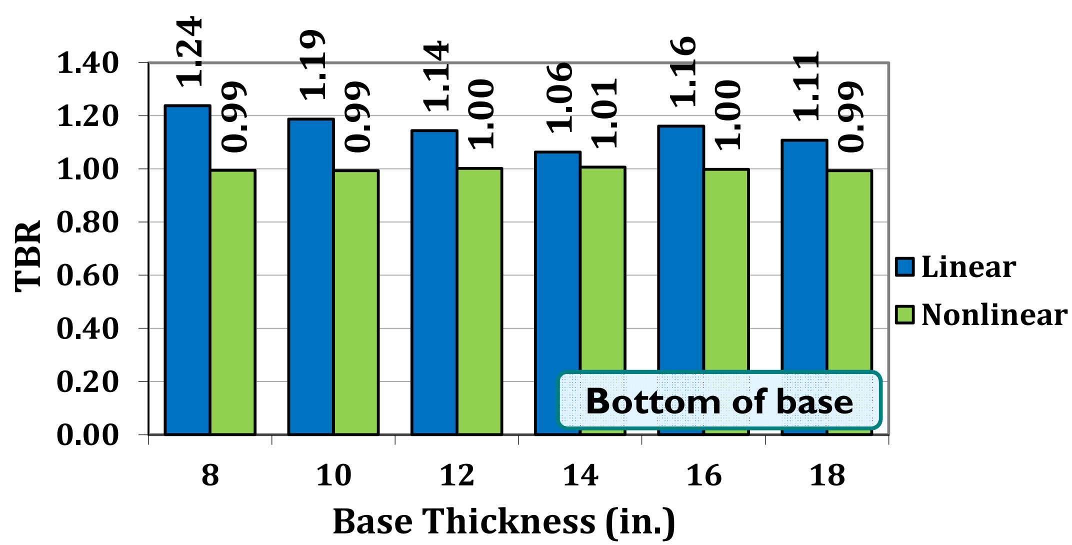




Linear Elastic vs. Nonlinear Modeling of Base and Subgrade

- Biaxial geogrid
- F-15 Aircraft
- Traffic Benefit Ratio (TBR)
  - 3-in. asphalt
  - Varying base thickness
- Similar pattern for C-17
- TBR decreased with respect to linear analyses

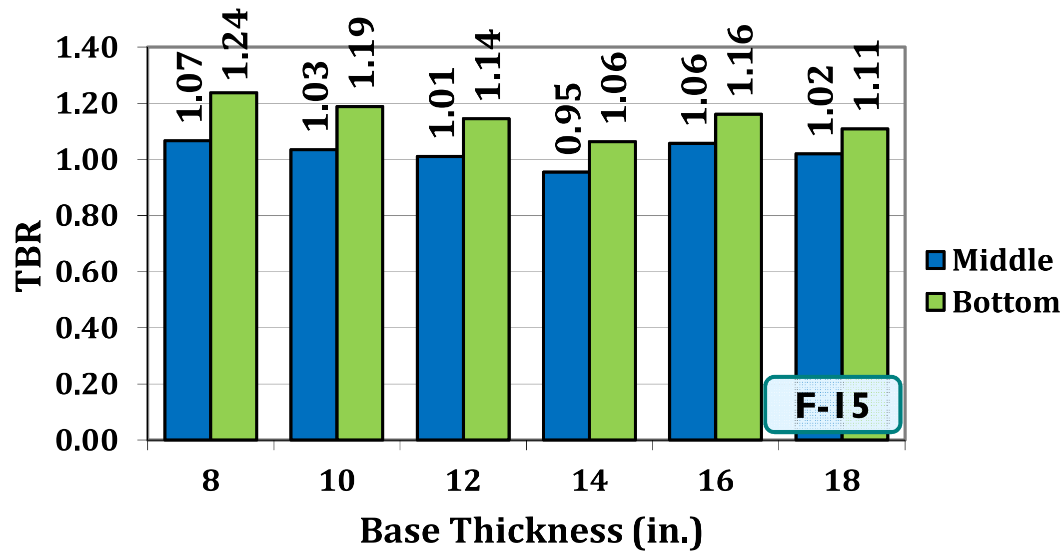


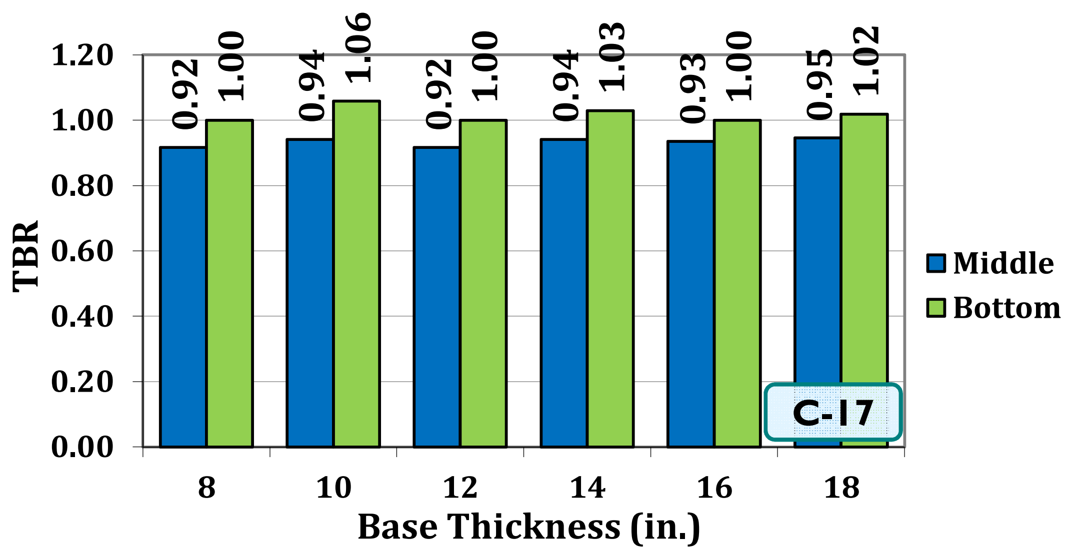


Layer	Nonlinear Parameters		
	k_1	k_2	k_3
Base	30,000 psi (207 MPa)	0.25	-0.25
Subgrade	5,000 psi (36 MPa)	0	-0.5

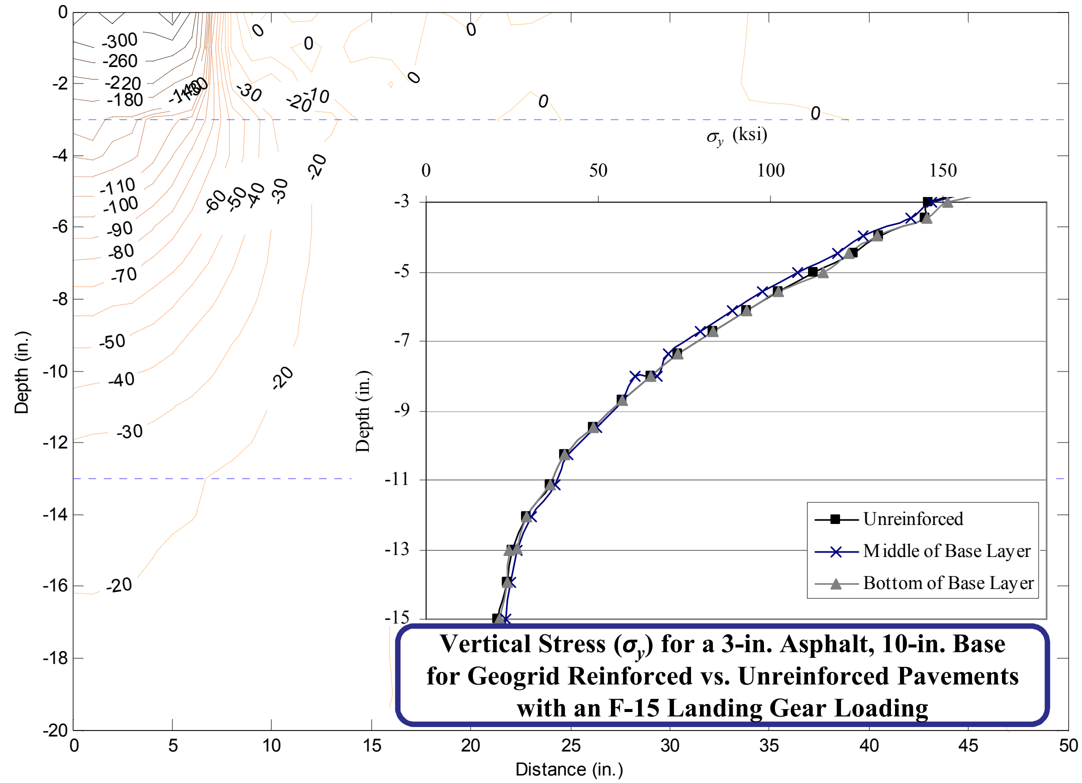
Impact of Base Thickness

- Traffic Benefit Ratio (TBR)
  - 3-in. asphalt
  - Varying base thickness
- Greater benefit observed when
  - Geogrid placed at bottom of base
  - F-15 aircraft
- Less benefit in thicker bases

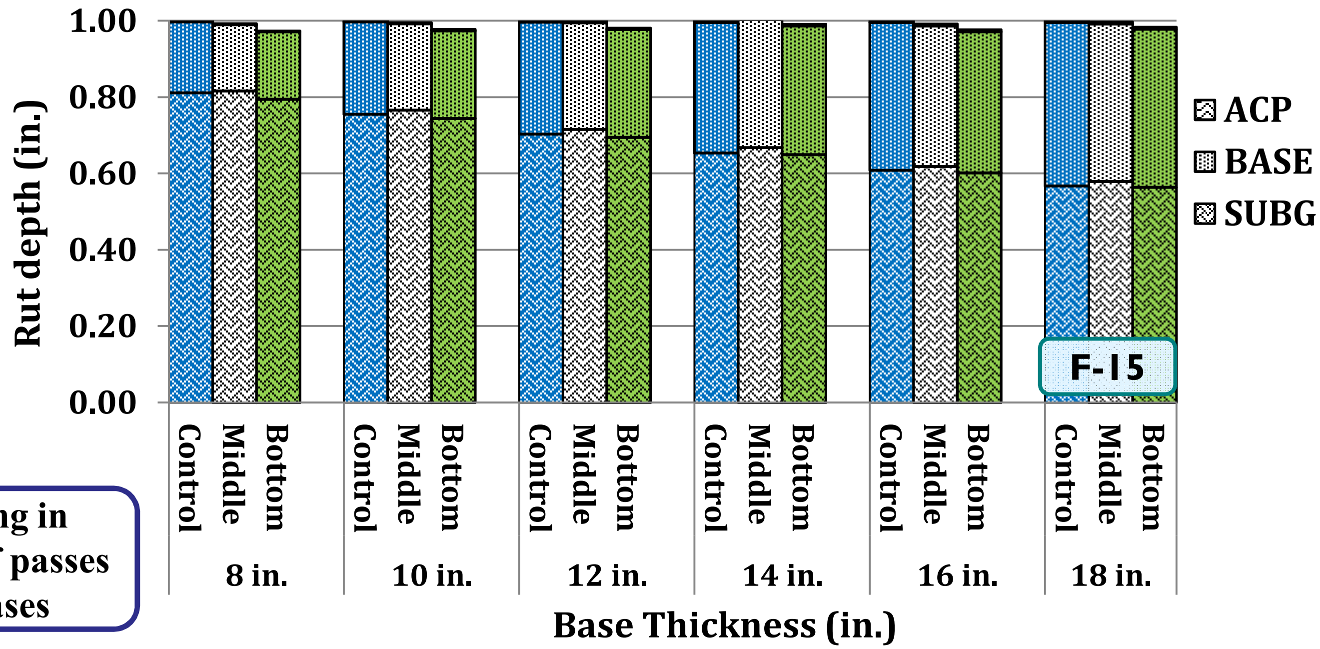




- Use of geogrid in the middle of the base transfers rutting from the base to the subgrade
- The proportion of rutting per layer remains the same when the geogrid is placed at the bottom of the base when compared to an unreinforced pavement.



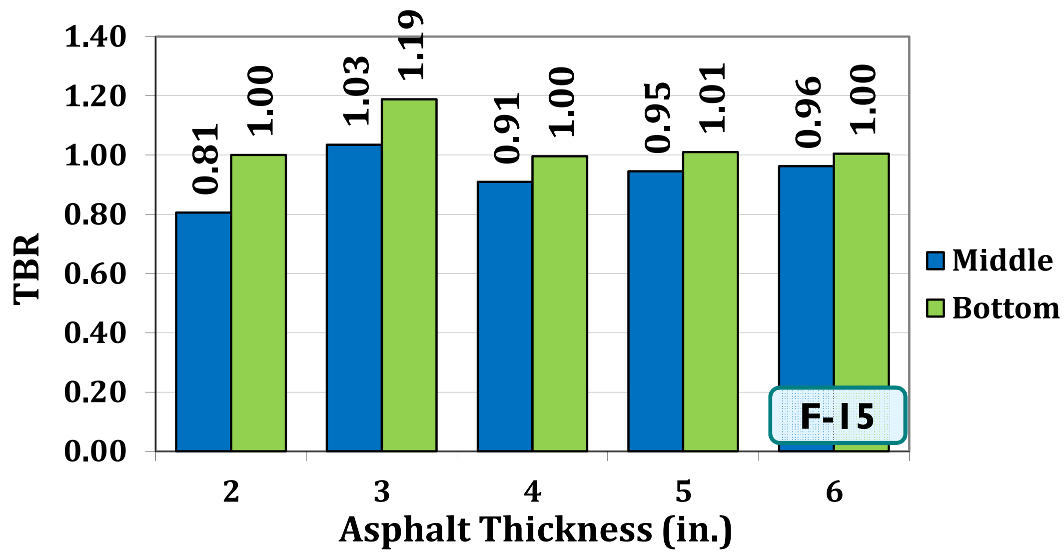
Vertical Stress (σ_y) for a 3-in. Asphalt, 10-in. Base for Geogrid Reinforced vs. Unreinforced Pavements with an F-15 Landing Gear Loading

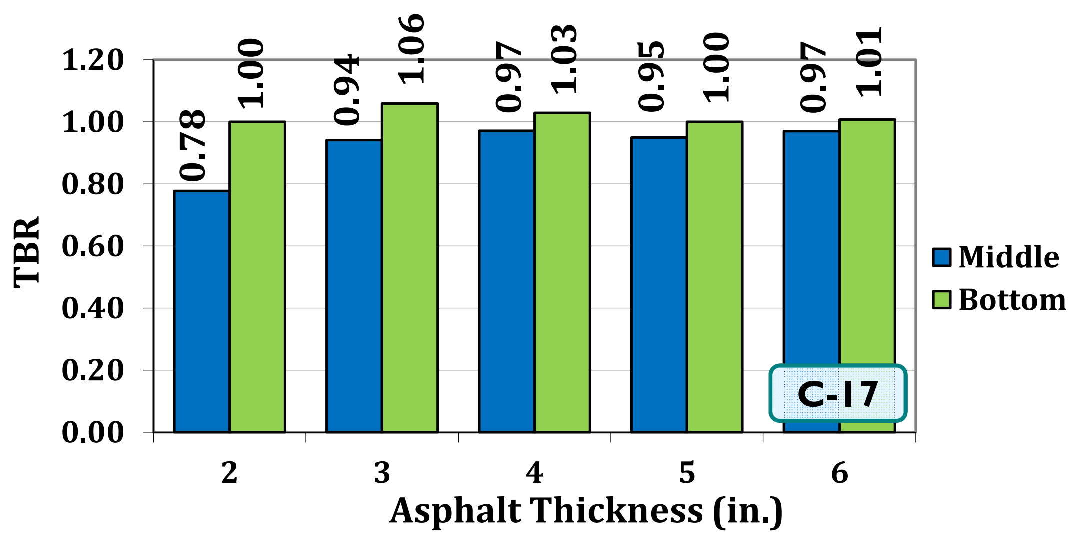


Amount of accumulated rutting in different layers at the number of passes to failure for unreinforced cases

Impact of HMA Thickness

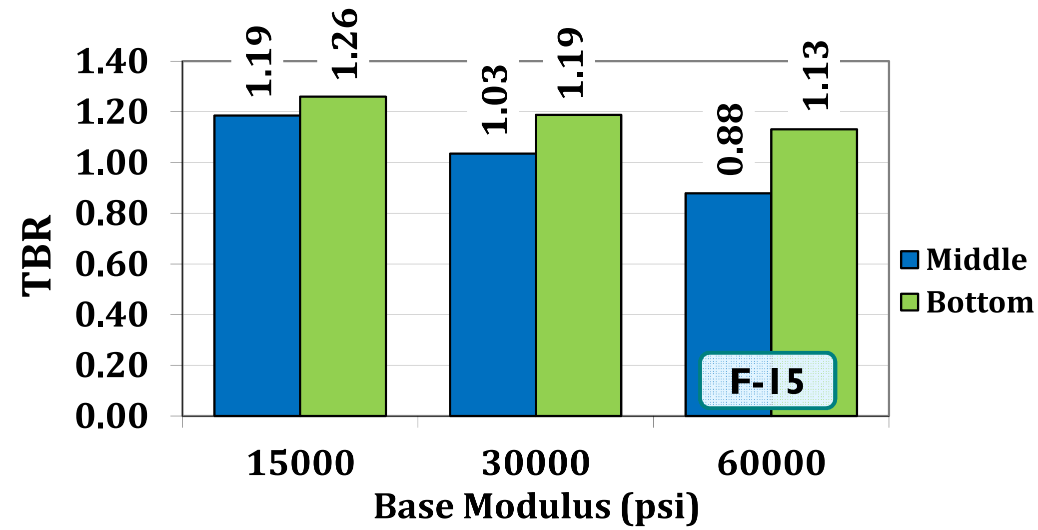
- Traffic Benefit Ratio (TBR)
  - Varying HMA thickness
  - 10-in. base
- Generally, no significant impact

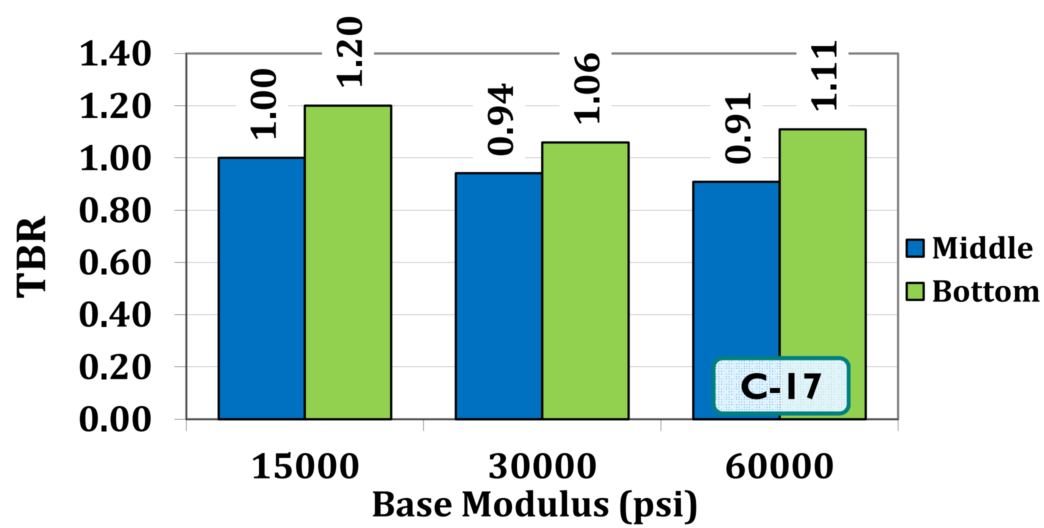




Impact of Base Modulus

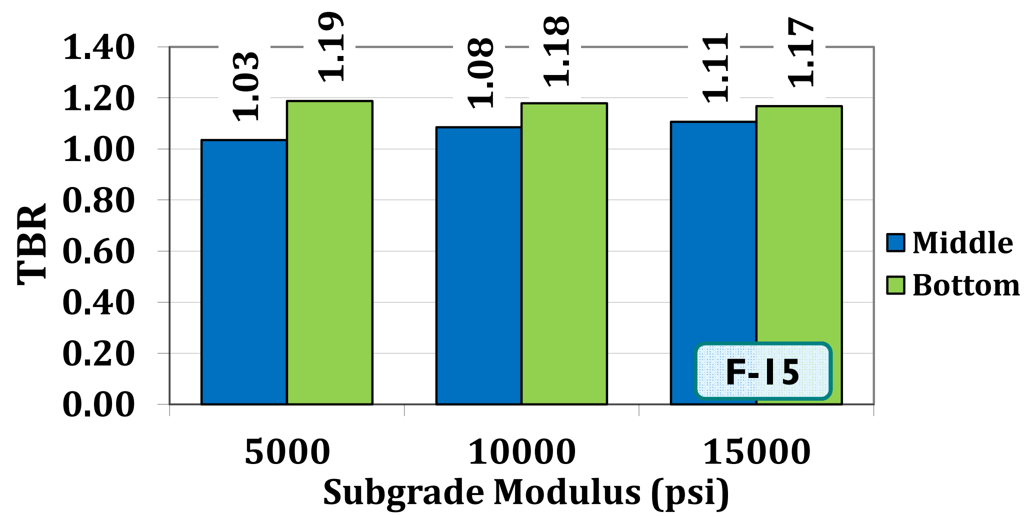
- Traffic Benefit Ratio (TBR)
  - 3-in. asphalt
  - 10-in. base
- Effectiveness of geogrid diminishes as the base layer becomes stiffer
- Greater benefit observed when
  - Geogrid placed at bottom of base
  - F-15 aircraft

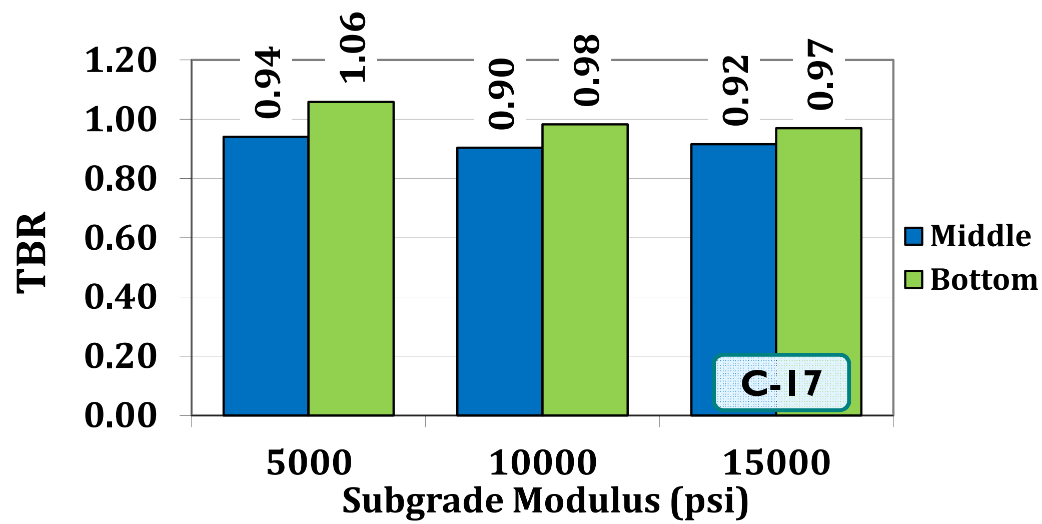




Impact of Subgrade Modulus

- Traffic Benefit Ratio (TBR)
  – 3-in. asphalt
  – 10-in. base
- Greater benefit observed when
  – F-15 aircraft
  – Geogrid placed at bottom of base for weaker bases
  – Geogrid placed in the middle of the base layer for stiffer bases





Summary and Recommendations

- TBR is moderately sensitive to HMA thickness
  - More significant for thinner HMA layers
- TBR is sensitive to thickness and modulus of the base mainly when reinforcement is below the base and an F-15 is considered
  - Benefit diminishes for thicker bases and is accentuated for less stiff bases.
- Effectiveness of geogrid reinforcement is significantly impacted by subgrade modulus
  - As the subgrade becomes stiffer, the percentage of rutting in the base layer increases.

Summary and Recommendations

- Benefit is more pronounced when an F-15 aircraft is considered moderate
- A significant component to the effectiveness of the geogrid is the type of the geogrid used as quantified by the soil/aggregate-geogrid interface shear stiffness
  - Particularly when the geogrid reinforcement is placed in the middle of the base.
  - Based on information available, the triaxial geogrid provides no added benefit when compared to the biaxial geogrid
  - This conclusion may change when more concrete information or standard test procedure become available about the interface shear stiffness.

Summary of Impact of Pavement Properties on TBR

		Aircraft Type			
		F-15		C-17	
		Location of Geogrid			
Property		Middle	Bottom	Middle	Bottom
Geogrid					
HMA	Thickness				
Base	Thickness				
	Modulus				
Subgrade	Modulus				
Soil/Aggregate-Geogrid Interface	Shear Stiffness				
Triaxial					
Base	Thickness				
Geotextile/Geomembrane					
Base	Thickness				

Not significant: 0.95 ≤ TBR ≤ 1.05

Moderately significant: 0.90 ≤ TBR < 0.95 and 1.05 < TBR ≤ 1.10

Significant: TBR < 0.90 and TBR > 1.10

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